



University  
of Glasgow

# HIGH FREQUENCY COMMUNICATION SYSTEMS

## Lecture 11

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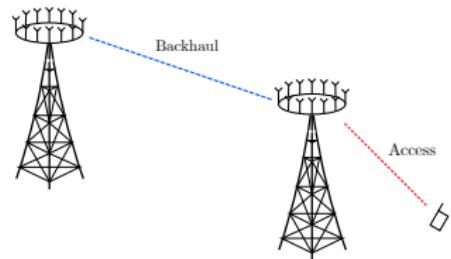
Figure 1: Survey available at <https://forms.office.com/r/uzegCvGdPE>.

- Terahertz Communications
- Terahertz Generation
- Plasmonics
- Applications of Terahertz

## TERAHERTZ COMMUNICATIONS

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- The electromagnetic (EM) spectrum between 0.1 THz to 10 THz is called the *THz band*.
- Naturally, higher carrier frequency yields higher bandwidth
  - Not necessarily higher channel capacity
- We can achieve bandwidths up to 20 Gbps
  - A typical 8K film requires 200 Mbps bandwidth!
  - For comparison, optical fibre communication can provide 39 Tbps bandwidth!
- THz communications provide a promising application for back hauling of base stations.



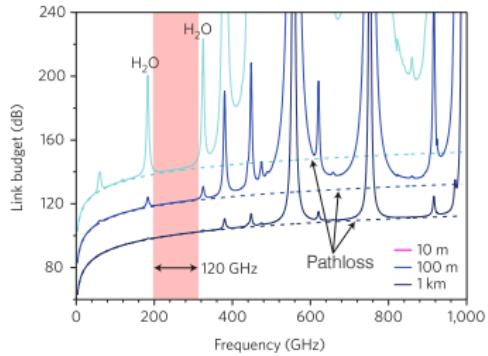
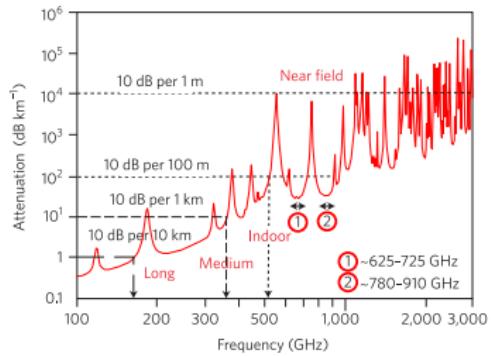
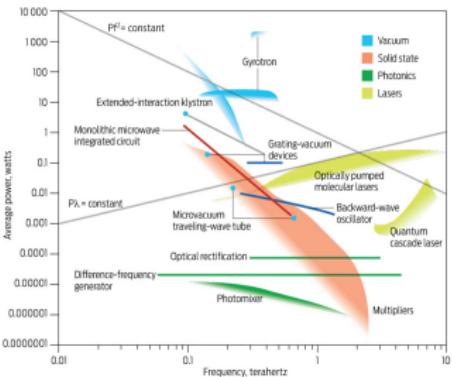
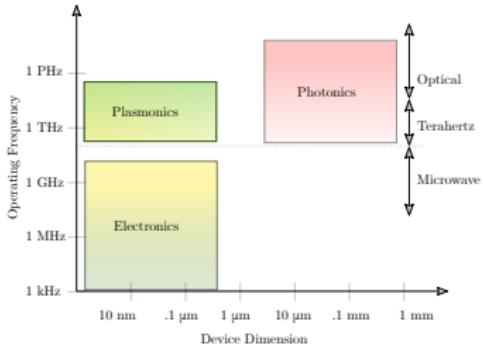


Figure 2: EM wave attenuation and free-space path-loss due to H<sub>2</sub>O molecules in the air in the THz spectrum [Nagatsuma, T., et al. Nature Photon 10, 371-379 (2016)].

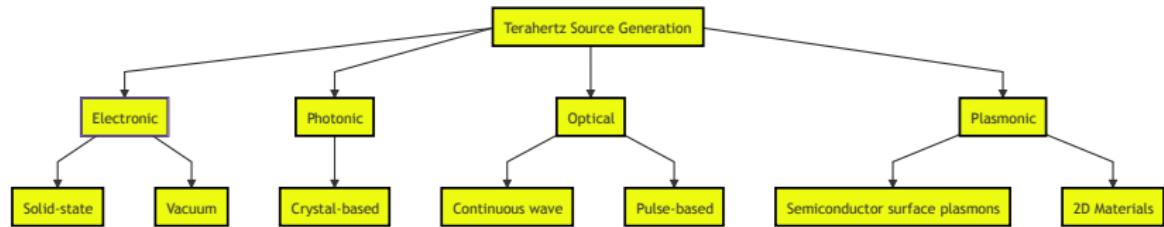
- Just like mmWave communications, THz waves have considerably high free-space pathloss
  - This requires even higher gain antennas ( $\sim 100$  dB)
- Current THz device technology does not allow us to increase the power levels
- Since THz lies in the middle of microwave and optical frequencies, we get the *best of both worlds*.
  - We have non-ionising waves
  - We can construct devices similar to optical technologies.



## TERAHERTZ SOURCES

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There are many ways to generate efficient THz signals. However, all the technologies have not fully developed to be widely available.



Today, we will focus on the plasmonic technologies.

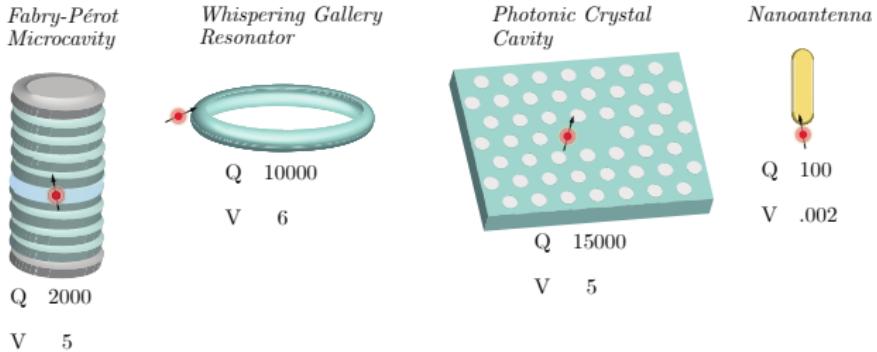


Figure 3: Different Source techniques at THz and optical frequencies.

- Microwave based vacuum tube technologies are extended to THz frequencies
  - The process involves conversion of modulated electron current to electromagnetic radiation
  - These are often called *fast-wave* devices
  - The phase velocity of the generated electromagnetic wave is greater than the speed of light

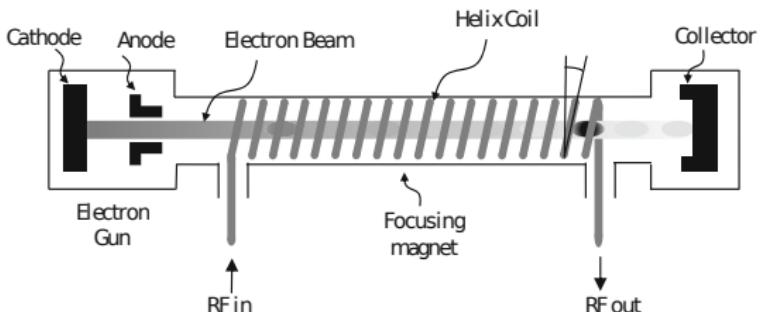
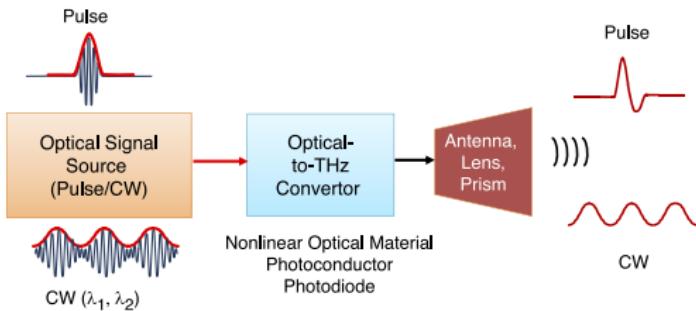


Figure 4: A typical vacuum-tube source [Rieh, J-S., Intro to Terahertz Electronics, Springer (2021)].



- The main idea is the optical-THz signal conversion through lasers
- Non-linear optical (NLO) materials are used to generate *monochromatic* THz waves
  - II-VI Semiconductor crystals such as ZnTe, and CdTe are commonly used as NLO materials

PLASMONICS

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- Interfacial wave phenomena
  - Metal-dielectric interface
  - Semiconductor heterostructure
- Surface plasmon polaritons (SPPs)
- Plasma frequency
  - Metals — Optical frequency
  - Semiconductors — Terahertz

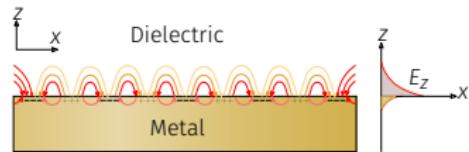


Figure 5: SPPs at optical frequencies

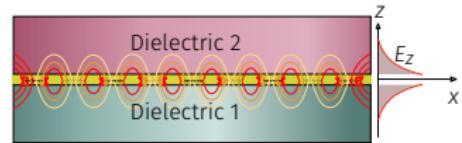


Figure 6: SPPs in the THz regime

- Slow surface waves
- Reduced Wavelength
- Focusing beyond the diffraction limit
- Optical SPP

$$\operatorname{Re} [\varepsilon_{\text{metal}}(\omega)] < 0$$

- THz SPP

$$\operatorname{Im} [\sigma_s(\omega)] < 0$$

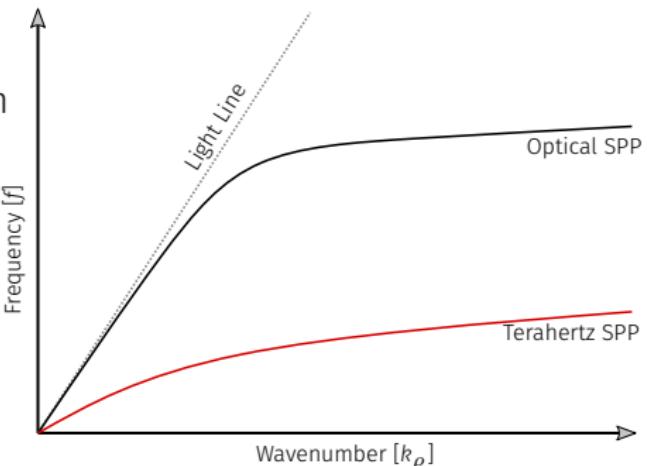


Figure 7: Dispersion Curve comparison

- Convert Localized near-field to efficient far-field radiation
- Low Q-factor
- Extremely small size
- High Purcell Factor

$$P = \frac{Q}{V}$$

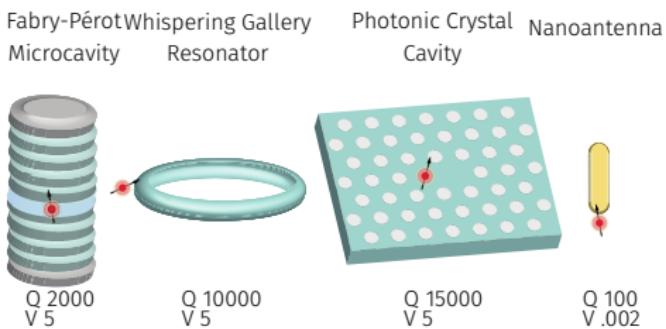
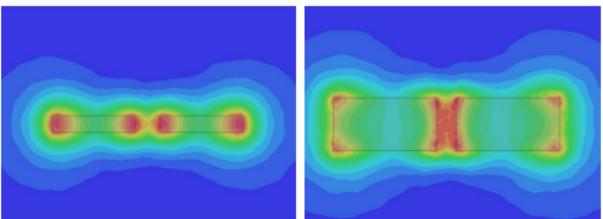
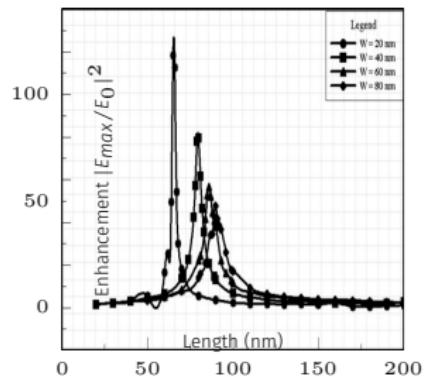
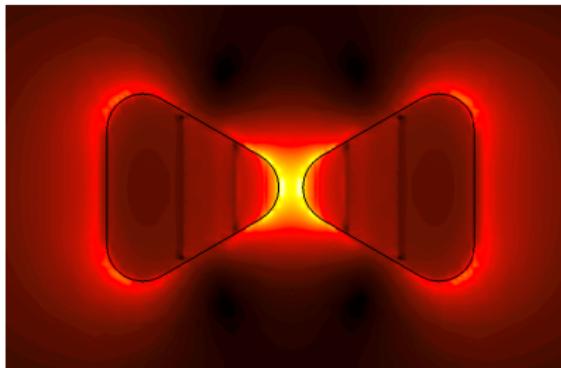


Figure 8: Optical resonant cavities for electric field enhancement

- Directive radiation

- Scaled-down microwave antenna designs
- Shift of resonance with width unlike in microwave regime



## TWO-DIMENSIONAL ELECTRON GAS (2DEG)

- Semiconductor Heterostructure in high electron mobility transistor (HEMT)
- High concentration of free electrons ( $\sim 1 \times 10^{11} - 1 \times 10^{14} \text{ cm}^{-2}$ )
- Very high Mobility ( $\sim 1 \times 10^3 - 1 \times 10^6 \text{ cm}^2/\text{V}\cdot\text{s}$ )
- Formation of Quantum Well
  - Two-dimensional confinement of electrons

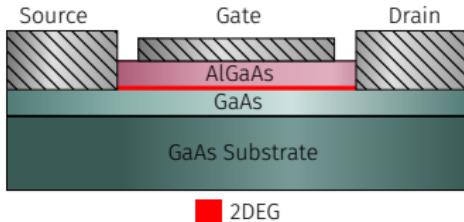


Figure 9: Typical GaAs/AlGaAs HEMT

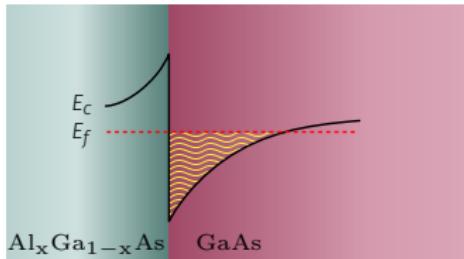
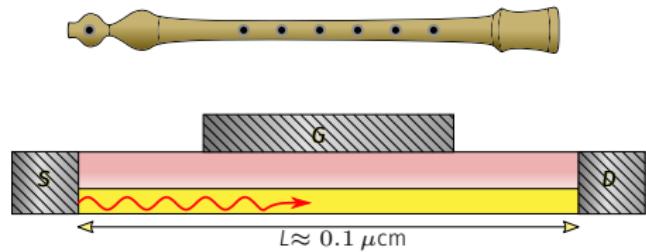


Figure 10: Band diagram of a GaAs/AlGaAs heterostructure

- Plasma waves in 2DEG
- Dyakonov-Shur instability
  - Voltage bias at source and drain terminals
  - Plasma resonance
  - THz emission
- Electronic Flute
  - Tunable resonance with gate voltage



$$\lambda = \frac{c}{f}$$
$$\implies 300\mu\text{m}$$

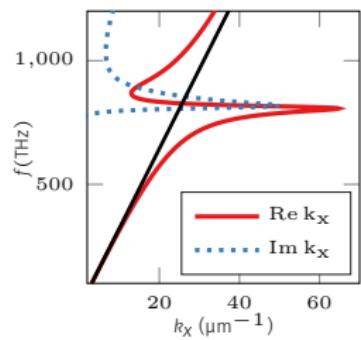
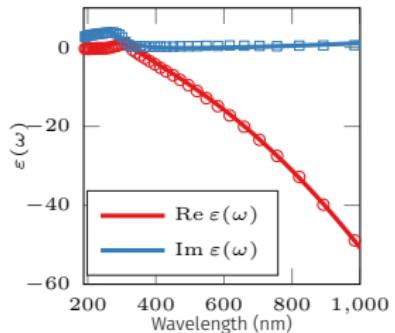
- SPP solution (pole expression)

$$k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_1 \varepsilon_2(\omega)}{\varepsilon_1 + \varepsilon_2(\omega)}}$$

- Accurate material description

$$\varepsilon_2(\omega) = \varepsilon_\infty - \frac{\omega_d^2}{\omega^2 - j\gamma\omega} + \sum_{i=1}^N G_i(\omega)$$

$$G_i(\omega) = C_i \left[ \frac{e^{j\phi_i}}{\omega_i + \omega - j\Gamma_i} + \frac{e^{-j\phi_i}}{\omega_i - \omega + j\Gamma_i} \right]$$



- Drude-Lorentz Surface Conductivity

$$\sigma_s = \frac{N_s e^2}{m^*} \frac{\tau}{1 + j\tau\omega}$$

$N_s$  - Surface charge density

$\tau$  - Scattering time

$m^*$  - Effective electron mass

- Equivalent Circuit

$$\sigma_s = \frac{1}{Z} = \frac{1}{R + 1/j\omega C}$$

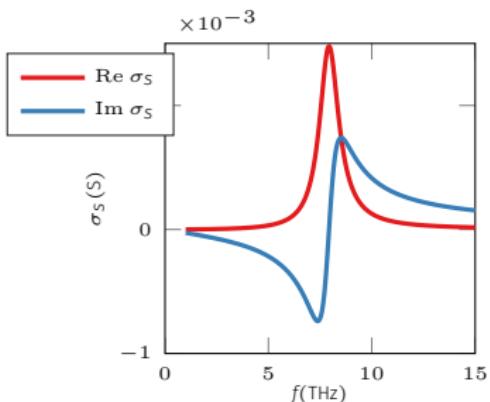
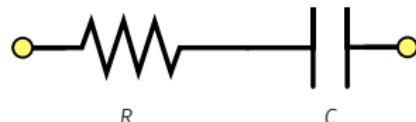


Figure 11: Room temperature  
GaN/AlGaN 2DEG surface conductivity

$$Z = R - \frac{j}{\omega C}$$



## DISPERSION RELATION FOR A 2D SHEET

- Conductive Sheet in free space
- TM mode surface wave

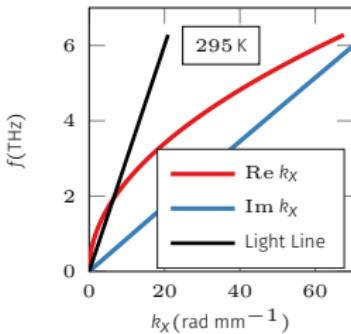
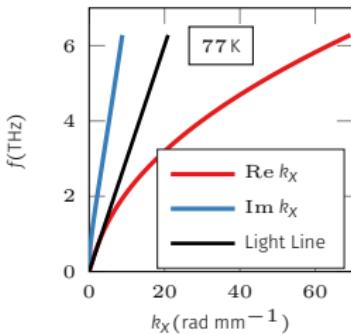
$$k_P^{\text{TM}} = \frac{\omega}{c} \sqrt{1 - \left( \frac{2}{\eta_0 \sigma_s} \right)^2}$$

- Below plasma frequency

$$\text{Im } \sigma_s < 0$$

- At low temperature

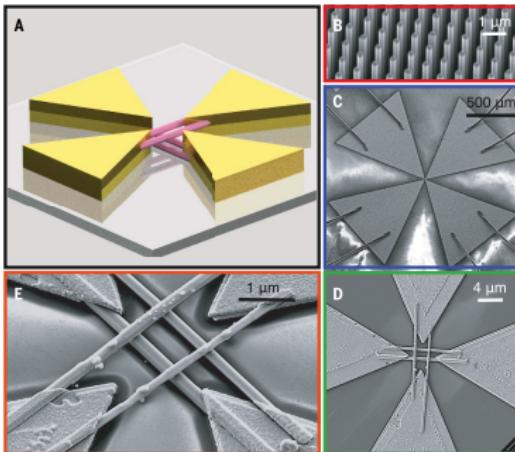
$$\text{Im } |\sigma_s| \gg \text{Re } |\sigma_s|$$



TERAHERTZ APPLICATIONS

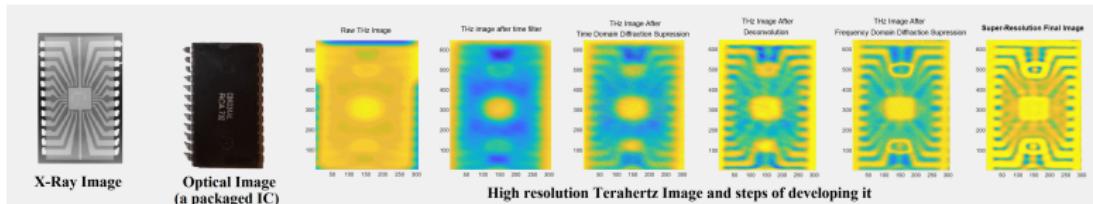
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Relying on the principle of reciprocity, we can use photoconductive antennas to detect THz radiation.

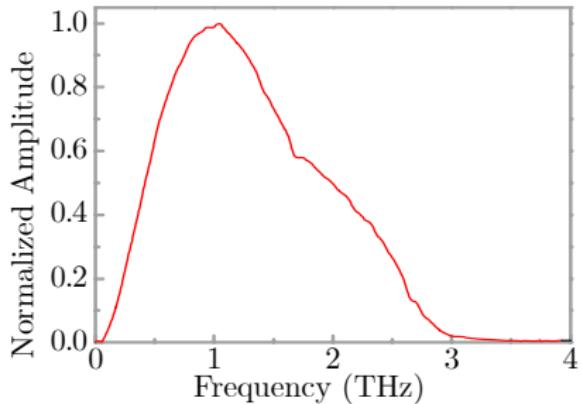


**Figure 12:** A polarisation sensitive cross-nanowire THz detector [Peng et al., Science 368, 510–513 (2020)].

- THz waves have the ability to **see through** apparently opaque objects.
- This is done in a non-ionising manner
- Through image processing, we can achieve high-resolution imaging through THz waves.



- THz time-domain spectroscopy (THz-TDS) is a well-known method for characterising the material properties of different substances
  - Attractive applications in explosives detection, counterfeit drug discovery and health monitoring of plants
- The Biggest feature is again, the non-ionising nature of THz waves
- Common substances such as H<sub>2</sub>O and N<sub>2</sub> have strong absorption spectra



2,4,6-Trinitrotoluene (TNT)

